Measuring Planck's Constant and Work Function of Barium Through Properties of the Photoelectric Effect

Nathaniel Herbert

Physics Department, University of Texas at Austin

Abstract

In our experiment, we were able to accurately measure Planck's constant and the work function of barium through properties of the photoelectric effect. By shining a mercury lamp on a thin sheet of barium in an isolated system, a current was created. By applying specific filters to the mercury lamp, various wavelengths were then isolated in the circuit. A voltage, applied in the opposite direction, was then used to measure the specific stopping voltage of the specified wavelength. A function of stopping potentials vs wavelengths was then obtained. Lastly, using modern interpretation of the photoelectric effect, coefficients were then obtained for both Planck's constant and the specific work function of the chosen metal. Our results give a value of $2.14 * 10^{-15} \pm 1.122 * 10^{-15}$J*s/C for h/e and $\Phi/e = 0.621 \pm .01$V for the work function of barium. This is comparable with the accepted values of $4.14 * 10^{-15}$J*s/C and 2.2V respectively.

1 Introduction

1.1 Physics Motivation

The photoelectric effect is an important phenomena in our current model of modern physics and an important applicable effect in current technology and applications. The experimental facts that can be deduced from photoelectric experiments are among the strongest evidence that the electromagnetic field is quantized. That is, the results cannot be explained if one assumes a continuous energy distribution in the radiation field.

Devices such as photomultipliers rely heavily upon the photoelectric effect. A photomultiplier by itself has an incredibly large number of applications such as film scanning, particle counting, and aiding with telescopes. [1] Clearly, the photoelectric effect has an important, and wide array of applications in the world of 21st century technology.

As such a fundamental part of our modern understanding of the natural world, it is extremely necessary to have accurate results to match the predictions made by this theoretical phenomena. For our experiment, we will be confirming Planck's constant and the work function of barium, the metal used as our photocathode in this experiment.

1.2 Theoretical Background

In the photoelectric effect, electrons are emitted from matter as a consequence of their absorption of energy from electromagnetic radiation. The photons of a light beam have a characteristic energy proportional to the frequency of the light. In the photoemission process, if an electron within some material absorbs the energy of one photon and acquires more energy than the work function (the energy used to bind the electron) of the material, it is ejected. If the photon energy is too low, the electron is unable to escape the material. Increasing the intensity of the light beam increases the number of photons in the light beam, and thus increases the number of electrons excited, but does not increase the energy that each electron possesses.

The amount of energy required to liberate an electron is related to the frequency of the photon. If the photon has enough energy to liberate the electron, the remainder of the energy from the photon is converted into kinetic energy for the electron. This idea can be expressed mathematically as

$$hv = KE_{max} + \Phi \tag{1}$$

where h is known as Planck's constant, v is the photon frequency, KE_{max} is the maximum kinetic energy of the electron, and Φ is the work function of the metal.

1.3 Our Approach

The photoelectric effect provides a current in a ciruit when electrons flow from the cathode to the anode of a metal. By supplying a current in the opposite direction of the flow of electrons coming from the photoelectric effect, one can accurately measure the maximum kinetic energy of the electrons from the photoelectric effect. This happens because when one supplies a potential in the opposite direction of the photoelectric effect, less and less electrons are able to complete the circuit. [2] When the current reaches 0, the electrons with the highest amount of kinetic energy can no longer complete the circuit. [3] This allows for the equation

$$e\left|V_s\right| = KE_{max} \tag{2}$$

where V_s is the stopping potential and e is the charge of an electron.

Plugging Eq. 2 into Eq. 1 results in

$$\left|V_s\right| = (h/e)\frac{c}{\lambda} + (\Phi/e) \tag{3}$$

where λ is the wavelength of the photon and c is the speed of light.

By applying a filter over a light bulb, we allow only specific frequencies of photons to pass through, allowing for accurate measurements of the stopping potential at specific wavelengths. Plotting multiple graphs of frequency vs. stopping potential, one could theoretically come up with a list of stopping potentials as a function of frequencies, and using Eq. 3, these points could be plotted to solve for Planck's constant and the work function. By repeating this process with a variety of different filters, (hence different wavelengths of light) we could find a more precise slope and hence a more accurate result for both Planck's constant and the work function.

This setup is a relatively simple one. This is important because it means we are only required to take a small number of measurements. It is in my personal opinion that the less steps to the solution, the more accurate result. This is because the less measurements required, the less errors one receives. The smaller number of errors in turn leads to the smallest possible propagation of errors.

2 Experimental Setup

2.1 Apparatus

Our entire experiment is confined to the measurement of a current through a simple circuit powered by the photoelectric effect. A source of photons, provided by an Hg lamp, specifically an Electro Technic Products Model ML-900 is placed through a filter and shined directly onto our cathode, a thin piece of barium mixed with a small amount of nickel. A variable power supply, made at the University of Texas was connected to the circuit to provide a voltage in the opposite direction of the photoelectric effect. The electrons, when they are able to, run through a Keithley 6485 picoammeter which measures the current of the circuit. The electrons then travel back around to the anode, and across to the cathode to form a complete circuit. Since the power supply has a manual lever, and therefore was highly inaccurate at this scale of precision, a BK Tool Kit 27507A multimeter with an accuracy of $\pm.005$V was attached in parallel around the power supply to accurate measure the voltage output. The entire apparatus can be viewed in Figure 1.

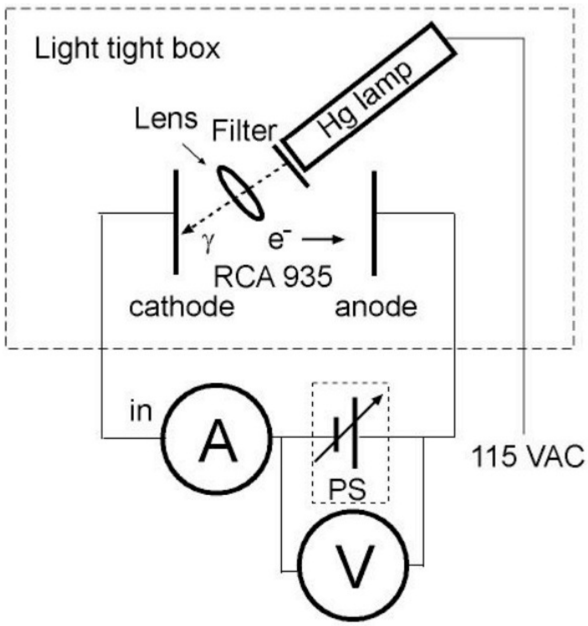

Figure 1: Schematic

2.2 Data Collection

First each filters was designated a specific wavelength. Using an Ocean Optic HR 2000 High resolution USB Fiber Optic spectrometer along with the program Spectra Suite, we were able to very accurately measure the specific wavelength each filter corresponded to. For certain filters, (specifically filter #'s 5406 and 5450) multiple, extremely close wavelengths were detected. In order to account for this, a weighted average was used to determine an average wavelength for the filter.

Our lamp was placed inside of a black box to prevent any external photons from interfering with the experiment. The lamp was turned on and allowed to heat up for 30 minutes before any measurements were taken. This was to ensure that the intensity of the lamp would not change during the experiment. A designated filter was then placed between the lamp and the cathode to allow only one specified wavelength at a time through to the metal.

The voltage was varied on the power supply to measure the change in current as a function of the applied voltage. Starting at roughly -2V depending on the wavelength, voltage was then increased at steps of roughly .1V until the current was sufficiently larger than 0. Measuring current proved excruciatingly difficult due to the extremely low current. Background noise was a huge factor and great care was taken to achieve accurate results. Measurements for current were taken 100 times and averaged together. This was repeated 5 times for each voltage and those results were then averaged together to achieve an accurate result for current. We then took these averaged measurements for current and plotted them against the applied voltages on a graph. The voltages where the current was measured to be 0 were dubbed the stopping potentials and plotted as a function of $(1/\lambda)$*c as specified by Eq. 3. This process was completed 5 times with 5 different wavelengths and the results were then graphed according to inverse wavelength vs. stopping potential.

3 Data Analysis and Results

3.1 Data Processing and Hypothesis Testing

Readings were taken for voltage in volts and current in nanoamperes. Polynomial fits of higher powers, usually around n=4 or 5 were used to find the closest fit around x=0. These values were then taken as close estimates for the stopping potentials V_s. The results of our calculations can be viewed in Table 1.

λ	v	$\lvert V_s \rvert$	$\sigma \lvert V_s \rvert$
4100	7.317e14	.926	.08
4412	6.799e14	.858	.009
5513	5.442e14	.532	.02
5750	5.217e14	.491	.015
5833	5.143e14	.484	.02

Table 1: Measured values for λ, $|V_s|$, and error for $|V_s|$

All 5 of our measurements for the stopping potential were then plotted against the frequency of their corresponding filter. A linear best fit was used to measure a slope and y-intersept. See figure 2.

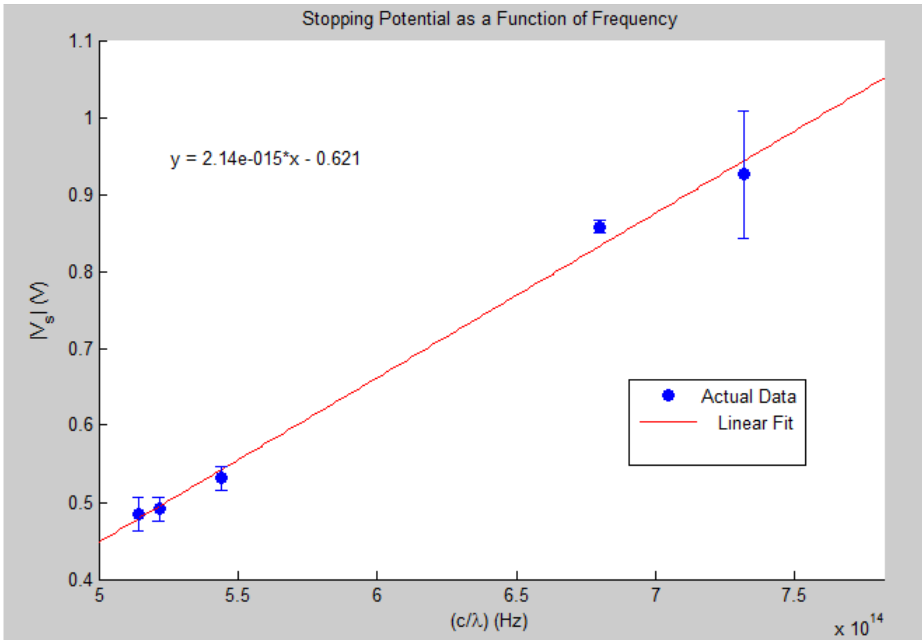

Figure 2: Plot of V_s as a function of (c/λ)

This graph provides a value $\frac{h}{e} = 2.14 * 10^{-15} \pm 1.122 * 10^{-15}$J*s/C and a work function Φ/e = 0.621±.01V. The accepted values for these results are $\frac{h}{e} = 4.14 * 10^{-15}$J*s/C and Φ/e = 2.2V

3.2 Results and Brief Discussion

Our results for $\frac{h}{e}$ and for our work function are $\frac{h}{e} = 2.14 * 10^{-15} \pm 1.122 * 10^{-15}$J*s/C and Φ/e = 0.621±.01V respectively. These results can be extrapolated from the graph in figure 2 using the properties of linear fits and Eq. 3. These values are comparable with the accepted values for these results of $\frac{h}{e} = 4.14 * 10^{-15}$J*s/C and Φ/e = 2.2V. Our results are off for $\frac{h}{e}$ by a factor of 48.3% and for the work function by a factor of 71.8%.

There were several sources of error is this experiment. First and probably the most significant is possible photoemission of the anode. This would result in a current traveling in the opposite direction in the circuit from the exact same photoelectric effect. This could explain the extremely low values we obtained across all wavelengths for the stopping potential, resulting in the huge error for the work function. Also accounting for error would be leakage current, which is where the capacitor in the experiment may gradually loss energy as electrons dissipate. This is known as dielectric leakage and is caused by a material not being a perfect insulator. [4]

Another source of error could come from our measurements of the allowed wavelengths of light through the specific filters. It is entirely possible that spectrometer we used to measure the wavelengths was not calibrated correctly. According to label on the spectrometer, the last time it had been calibrated was the year 2004. This would lead all of our wavelengths to be measured incorrectly. This error should however, only affect the work function since the error is systematic in nature, resulting in no difference to the slope of our graph.

4 Summary and Conclusion

Though our values for $\frac{h}{e}$ and Φ/e are off by roughly 48.3% and 71.8% respectively, we are at least within the ballpark of what is expected with our maximum error bar analysis. With more professional equipment and error analysis I believe a better construction of these values could be constructed.

I would like to thank Spencer Jolly my TA for helping me and my partner with our project. I would especially like to thank my partner in this experiment Jim Pharr, for his incredible help in both the lab and with my understanding of MatLab. I would also like to thank MatLab for the wonderful graphs. Lastly, I would like to thank you, the grader, for taking the time to check my work and helping expand my knowledge of writting lab reports.

5 References

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